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SOME EXPERIMENTAL STUDIES ON AIRJET AND SOLID BODY VORTEX GENERATORS

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ABSTRACT: Experimental studies have been carried out to characterize the flow around air jet and solid body vortex generators (VGs) in an induction type wind tunnel. While the former comprised a convergent nozzle having an area ratio of 4, the later ones included vane and wedge type devices. The studies were basically aimed to determine the downstream boundary layer profiles and the field of influence of the vortices to correlate their effectiveness in the control of rotating stall in a high speed axial flow compressor stage. The simulated studies in the wind tunnel were carried out at three free stream Mach numbers of 0.2, 0.35 and 0.5. Measurements with conventional probes were supplemented by flow visualization studies. Both the vane type VGs in counter-rotating configuration and the wedge type VGs appeared to give out strong pairs of counter-rotating vortices. The range of downstream influence increased with increase in free stream Mach number. The air jet showed strongest influence in locally energizing the downstream boundary layer. Subsequent studies in an axial compressor also showed that air jet was more effective than solid body VGs in energizing the boundary layer approaching the rotor, thus delaying separation and onset of rotating stall.

I. INTRODUCTION

Rotating stall is known to be an inherent characteristic of axial compressors, limiting their range of stable operation. The adverse pressure gradient across the machine leads to thickening of end wall and blade boundary layers. As the flow rate is reduced at constant speed, the loading increases and the higher incidence on the rotor blades causes the boundary layer to separate, thus giving rise to phenomenon of rotating stall. It is thus logical to consider suitable means of energising the boundary layers in order that they sustain a greater adverse pressure gradient and permit a larger change in incidence angles.

Solid body vortex generators in a variety of shapes have been successfully used for eliminating separation on wings and diffuser passages[1]. A most comprehensive reference on these boundary layer control devices is that of Lachman[2]. It deals with the mechanism, type and design criteria for VGs. It is shown that the vortices trailing longitudinally over the surface promote mixing of high momentum fluid in the free stream with low momentum fluid in the boundary layer, thus inhibiting separation. The use of VGs to control the casing and blade boundary layers in a high speed axial compressor stage was reported by Law et al[3] and Wennerstrom[4]. Vane type VGs, mounted on the casing and staggered in the same direction as the rotor blades, yielded marginal improvement in overall efficiency and stall margin.

Air jets can be generated by either a nozzle formed in the surface at some skew angle to the free stream flow and some inclination to the surface or they can be generated by solid body nozzles placed within the boundary layer. In either case they energise and impart momentum to the boundary layer, thus delaying separation under adverse pressure gradient. However, in a study conducted by Wetzel and Simpson[5] the air jets were found to be less effective than fin type VGs in delaying cross flow separation. On the other hand, the jets have been shown to be successful in delaying stall in a low speed compressor by Day[6]. Orientation and geometry of the jets are also the factors governing their effectiveness.

Control of end wall boundary layers and hence the stall, using VGs or air jets, has not been tried very seriously in high speed axial compressors. The present studies were aimed to explore the usefulness of these devices in a high speed compressor stage. Keeping in view the complex nature of flow in the rotating machines and in order to optimise the design of VGs or air jets, it was imperative to characterise the flow around these devices. Simulated studies were carried out on two designs of VGs and one design of airjet in an induction wind tunnel. Results of boundary layer behaviour, field of influence of the control devices and the vortex generation, obtained through conventional measurements and oil flow visualization, are presented and discussed. Effectiveness of these control devices, as seen in a high speed compressor test rig, is also presented.

II. BOUNDARY LAYER CONTROL DEVICES

2.1 Vortex Generators

Two types of vortex generators, viz. straight vane type, designated as VG-3 (Fig. 1a&b) and wedge type, designated as VG-4 (Fig. 1c), were tested. The reference dimension (height, h, of the VGs) was taken as 8 mm, which was equal to the measured boundary layer thickness at inlet to the compressor rotor. Rules for fixing the other dimensions were taken from Lachman[2]. The coordinate system X, Y, Z denotes streamwise, transverse and pitchwise direction respectively.

2.2 Air Jet

The air jet comprised a convergent nozzle of area ratio 4 with appropriate throat diameter (Fig. 1d). The aim was to get a high velocity (sonic) stream of air at the exit with suitable pressure ratio, keeping the volume flow rate low. The jet nozzle was silver brazed to a plug having provision for connection to a high pressure air supply line.

III. EXPERIMENTAL SET-UP

The simulated studies on VGs and air jets were conducted in a 0.25mx0.1m test section Induction Wind Tunnel[7]. One of the two circular side plates of the test section had provision for mounting an array of VGs or a single air jet (Fig. 2a&b). A number of static pressure plugs with 0.5 mm pressure tappings were arranged along the streamwise centre line of the plate. Boundary layer measurements could be carried out by removing any of these static pressure plugs and fixing a suitable probe in that location.

Tests were carried out at three free stream Mach numbers of 0.2, 0.35 and 0.5. The straight vane type VGs were configured both in co-rotating and counter-rotating vortex arrangement. The wedge type VGs, by their construction, were to produce counter-rotating vortices only. As for the air jet, a single device was fixed in the tunnel side plate with the jet issuing in the streamwise direction. Wall static pressures and boundary layer profiles were obtained at three locations downstream of the VGs and airjet. Similar measurements in the empty tunnel were made to form the base-line data. Oil flow patterns were also obtained at all the above test conditions.

The compressor test facility[8] comprised a transonic compressor stage with 21 rotor blades and 18 stator blades. The design pressure ratio, mass flow rate and adiabatic efficiency were 1.35, 22 Kg/sec and 0.89 respectively. The design rotor tip Mach number was 0.9. A schematic layout of the flow path geometry and measurement planes is given in Fig.3. The instrumentation used in this investigation was conventional and comprised total pressure rakes for overall compressor performance and probe surveys for blade element performance.

The VGs and airjets were located on the inner wall of the compressor casing, upstream of the rotor, at a distance of about 50 mm from the rotor tip leading end (Fig.3). A total of 60 VGs and only 7 air jets were used in the present studies. Where as the circumferential spacing of VGs was based on the guidelines given by Lachman, the choice of the number of air jets was quite arbitary. The emphasis of the experimental investigation was to examine the effectiveness of these boundary layer control devices in delaying the onset of compressor stall. The VGs were oriented both in co- and counter-rotating vortex modes. The airjet nozzles were supplied with high pressure air from a separate compressed air source. The blowing pressure varied from 2 to 3 bar during the experiments. Data was collected for overall performance characteristic of the compressor stage, giving information on extended mass flow range.

IV. RESULTS AND DISCUSSION

As mentioned earlier, the wind tunnel studies were carried out at free stream Mach numbers of 0.2, 0.35 and 0.5. The corresponding Reynolds numbers, based on height (h) of the VGs, ranged from 0.36×10^5 to 0.89×10^5. However, the results obtained at Mach number of 0.35 only are discussed here.

4.1 Wall Static Pressure

There is no significant change in tunnel wall static pressure in the presence of VGs and airjet, as shown in Fig. 4a & b. The same trend was observed at other test Mach numbers.

4.2 Boundary Layer and Airjet Profiles

Boundary layer and airjet profiles at a location about 54-58 mm downstream (6.5 h in case of VGs and 18 d in case of airjet) are presented in Fig.5. These are to be analysed in conjunction with the oil flow patterns of Fig.6. The thinning of the boundary layer behind the diverging passages of VG-3 and VG-4 (Fig. 5a) and its thickening behind the converging passage of VG-3 and line of symmetry of VG-4, are quite typical of counter-rotating vortices generated by these devices. This is also evident from the oil flow patterns of Fig. 6b&c. The direction of rotation of the vortices is such as to give a velocity towards the surface behind the divergent passage and away from the surface behind the convergent passage. The enhanced mixing of low energy boundary layer fluid with the free stream flow causes the former to energise and tolerate adverse pressure gradients. The co-rotating arrangement of VG-3 also produces vortices, as indicated by Fig. 6a. However, these do not move in the free stream direction, but in a slightly curved path. Measurements at other streamwise locations have shown that the distortion in velocity profiles grows with the distance, indicating a growth in the size of the vortices. Also the vortices appeared to be stronger as free stream Mach number increased.

The airjet profiles in transverse direction for various blowing pressures are shown in Fig 5b. The jet velocity increases in the presence of main flow and with increasing blowing pressure. However, it was observed to decrease with increase in streamwise distance. The jet velocity profile is close to parabolic with peak velocity at about 3mm from the wall. The spread of the jet in the presence of the main flow (M=0.35; blowing pressure 2 bar) can be seen in Fig. 6b.

4.3 Effect on Compressor Performance

The overall performance of the compressor stage at 80% design speed is shown in Fig. 7. A slightly lower pressure rise in case of VG-4 was traced to a relatively higher rotor tip clearance. The VGs, either in co- or counter-rotating configurations, do not show any improvement in stall margin. It is surprising because the same devices, when tested in the wind tunnel, produced strong vortices. And these should have helped in energizing the compressor casing boundary layer as well. It could be that the separation of highly loaded blade boundary layer also plays a significant role in initiating stall and the energization of the casing boundary layer by VGs is not adequate to delay the onset of stall. On the other hand, the airjets appear to be quite effective in controlling stall in that the stall mass flow rate is reduced by almost 4.5%. The discretely spaced jets of high velocity air energise the incoming casing as well as blade boundary layers and prevent any incipient stall to grow. The jet mass flow rate was remarkably low at about 0.1% of the stall flow rate.

V. CONCLUSION

The simulated studies on VGs and airjets in a wind tunnel have been conducted to get an insight into the flow around these boundary layer control devices. While VGs were found to generate strong vortices, the airjets produced high velocity air streams. Tests in a compressor stage showed that the VGs could not bring about any enhancement of stable operating range by effecting boundary layer control. However, the airjets could produce significant improvement in compressor stall margin. It may be noted that the VGs have been successfully used in diffusers, air intakes, etc. Hence their successful implementation in compressors calls for more parametric studies, both in wind tunnel and rotating test rigs.

VI. ACKNOWLEDGMENT

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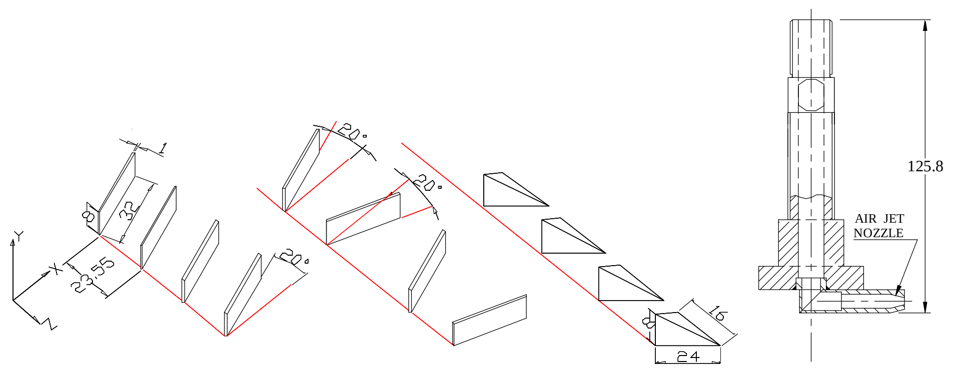
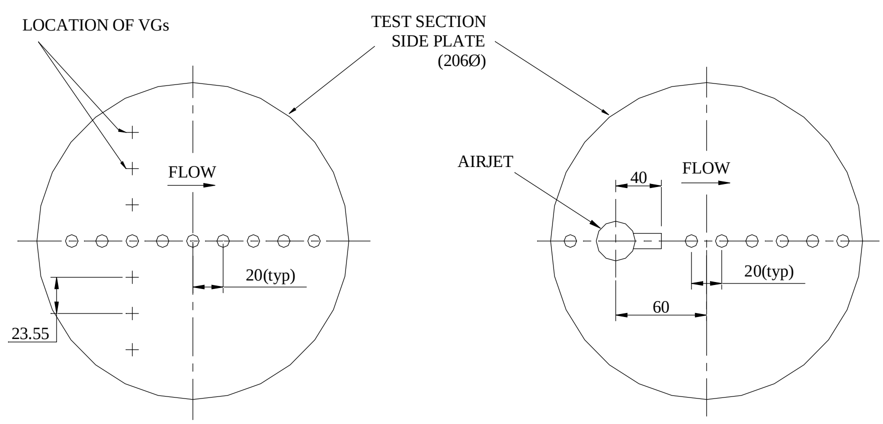


(a) VG-3 in corotating configuration
(b) VG-3 in counter rotating configuration
(c) VG-4 in counter rotating configuration
(d) Air jet plug

Fig. 1 Vortex generator configurations and airjet



(a) For vortex generator
(b) For airjet

Fig.2 Schematic of induction tunnel test section side plate showing location of VGs / Airjet and measurement points

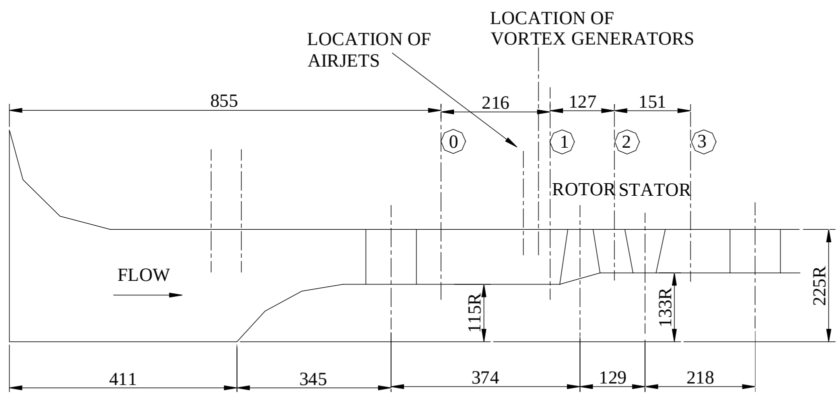
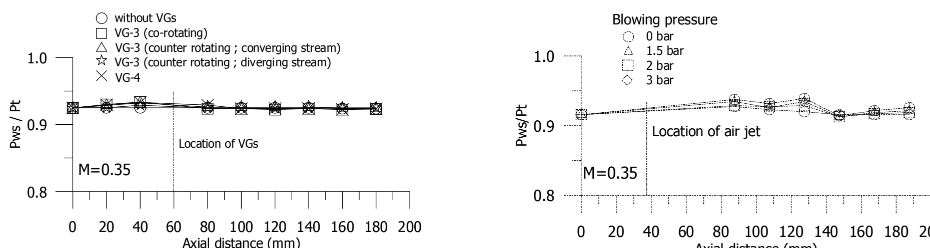


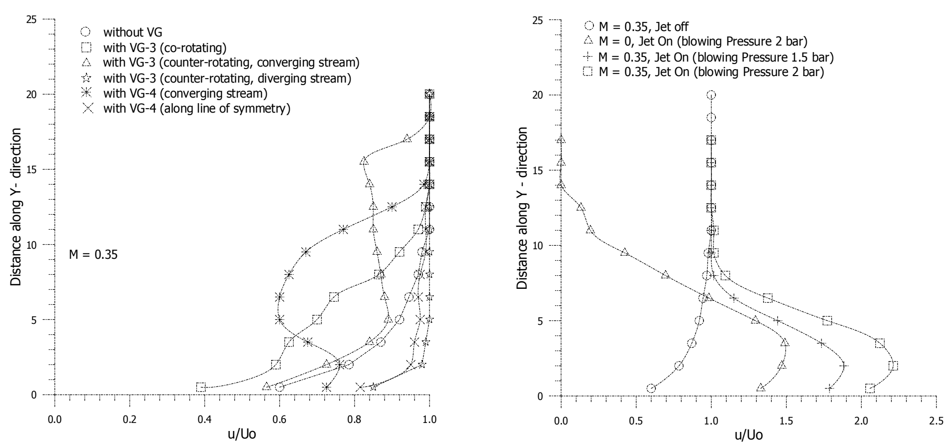
Fig. 3 Flow path geometry of compressor stage



(a) in the presence of VGs

(b) in the presence of air jets

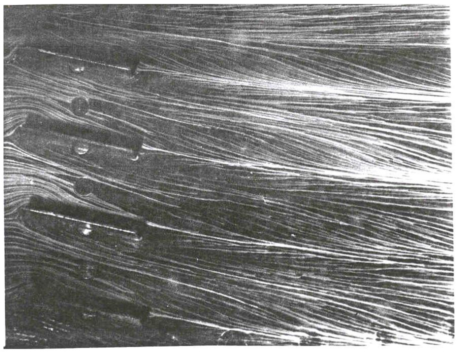
Fig.4 Streamwise variation of tunnel wall static pressure



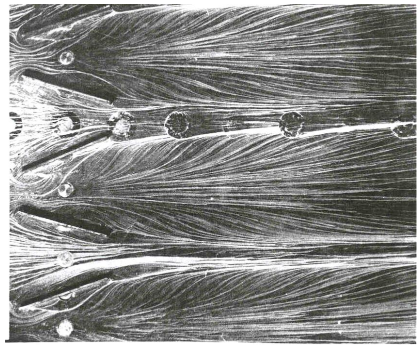
(a) in the presence of VGs
[54 mm from trailing end of VG]

(b) in the presence of air jets
[58 mm from end of air jet nozzle]

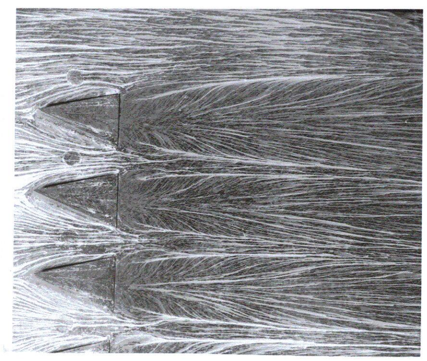
Fig.5 Boundary layer profiles downstream of VGs and airjet



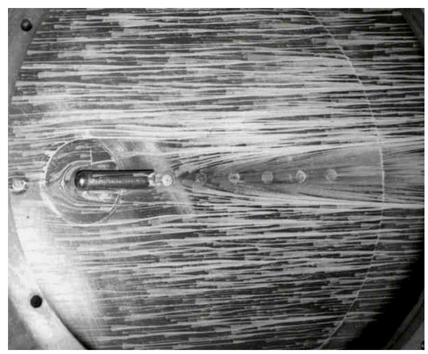
(a) VG-3 (Co-rotating)



(b) VG-3 (Counter-rotating)

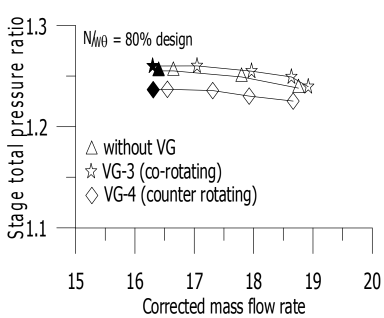


(c) VG-4 (Counter-rotating)

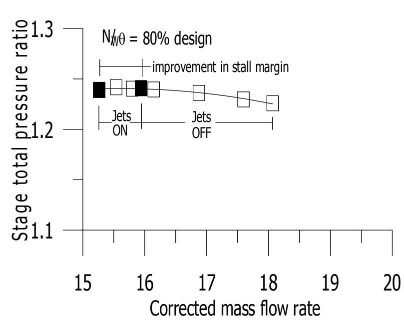


(d) Airjet (blowing pressure 2 bar)

Fig.6 Oil flow patterns in the presence of VGs and air jets at a free stream Mach number of 0.35 (Flow direction from left to right)



(a) in the presence of VG



(b) in the presence of air jets

Fig.7 Overall performance of axial compressor stage (filled symbols indicate stall point)